Reflection and Refraction of Light

Outline

- Light as E-M Wave; The E-M Spectrum
- The Ray Model of Light
- Reflection; Image Formation by a Plane Mirror
- Formation of Images by Spherical Mirrors
- Index of Refraction
- Refraction: Snell's Law
- Visible Spectrum and Dispersion
- Total Internal Reflection; Fiber Optics
- Refraction at a Spherical Surface

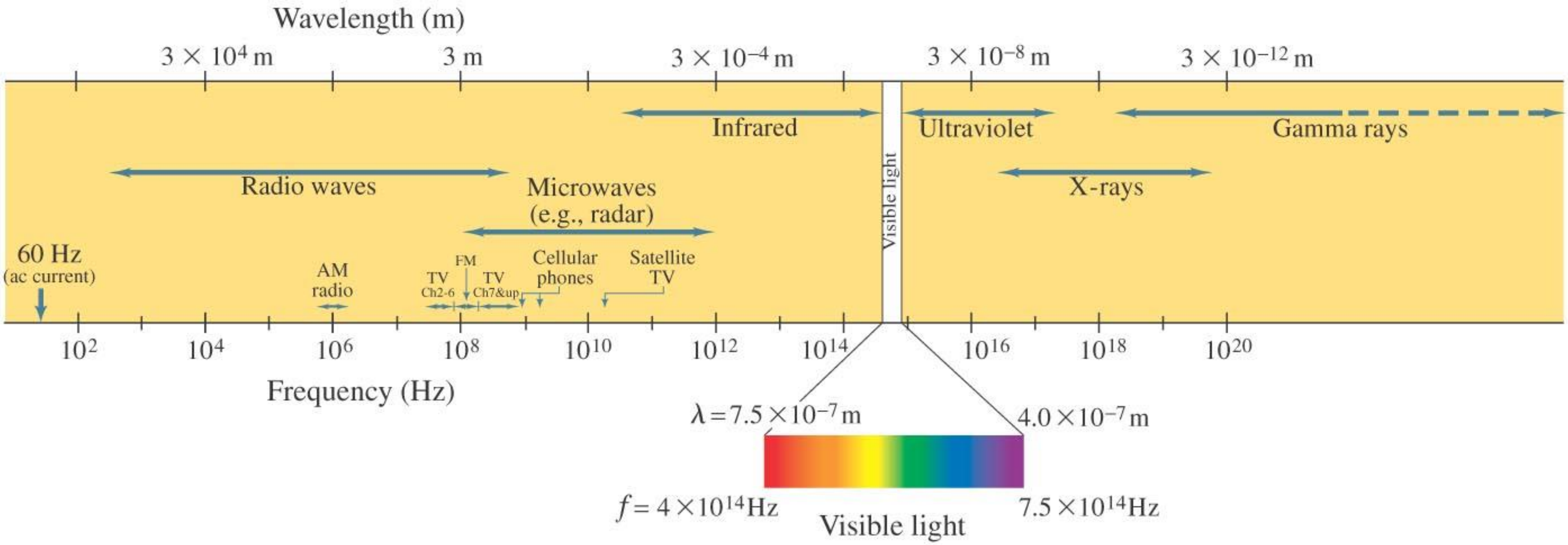
31-6 Light as an Electromagnetic Wave and the Electromagnetic Spectrum

The frequency of an electromagnetic wave is related to its wavelength and to the speed of light:

$$c = \lambda f.$$

31-6 Light as an Electromagnetic Wave and the Electromagnetic Spectrum

Electromagnetic waves can have any wavelength; we have given different names to different parts of the wavelength spectrum.



31-6 Light as an Electromagnetic Wave and the Electromagnetic Spectrum

Example 31-3: Wavelengths of EM waves.

Calculate the wavelength

(a) of a 60-Hz EM wave,

(b) of a 93.3-MHz FM radio wave, and

(c) of a beam of visible red light from a laser at frequency 4.74×10^{14} Hz.

31-6 Light as an Electromagnetic Wave and the Electromagnetic Spectrum

Example 31-4: Cell phone antenna.

The antenna of a cell phone is often ¼ wavelength long. A particular cell phone has an 8.5-cm-long straight rod for its antenna. Estimate the operating frequency of this phone.

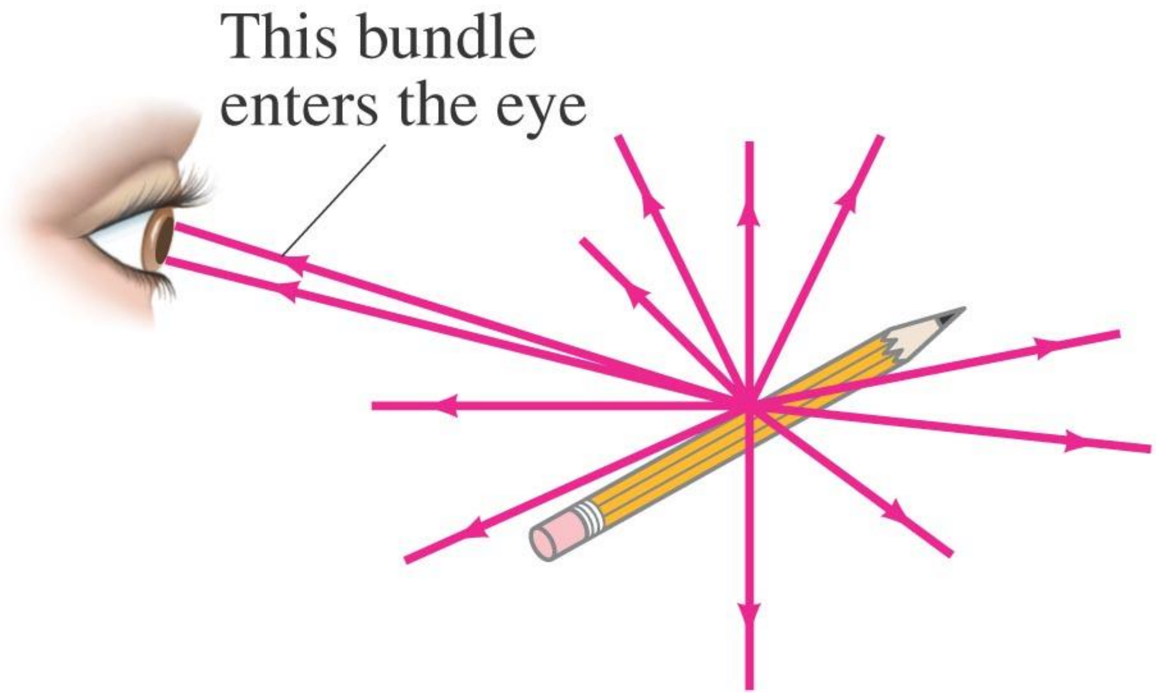
31-6 Light as an Electromagnetic Wave and the Electromagnetic Spectrum

Example 31-5: Phone call time lag.

You make a telephone call from New York to a friend in London. Estimate how long it will take the electrical signal generated by your voice to reach London, assuming the signal is (a) carried on a telephone cable under the Atlantic Ocean, and (b) sent via satellite 36,000 km above the ocean. Would this cause a noticeable delay in either case?

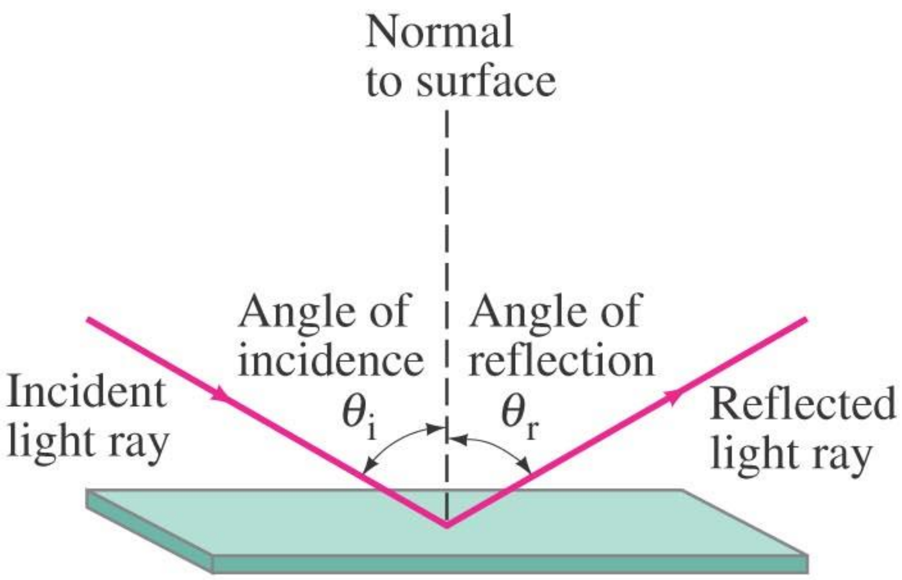
32-1 The Ray Model of Light

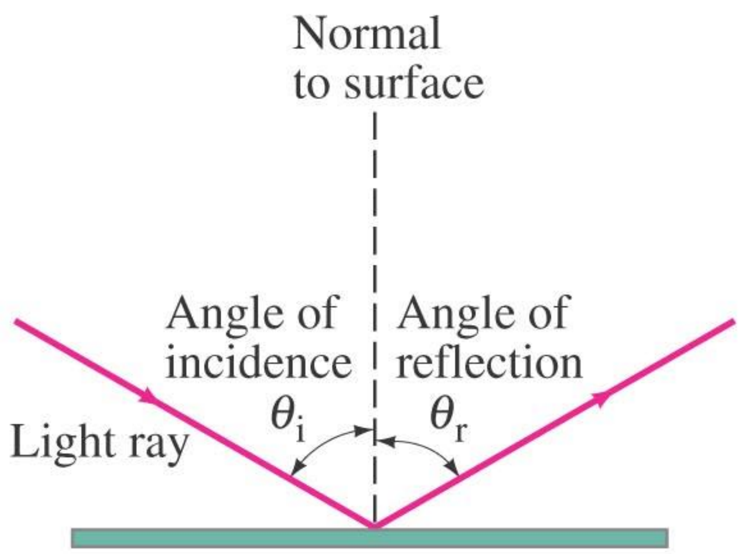
Light very often travels in straight lines. We represent light using rays, which are straight lines emanating from an object. This is an idealization, but is very useful for geometric optics.



32-2 Reflection; Image Formation by a Plane Mirror

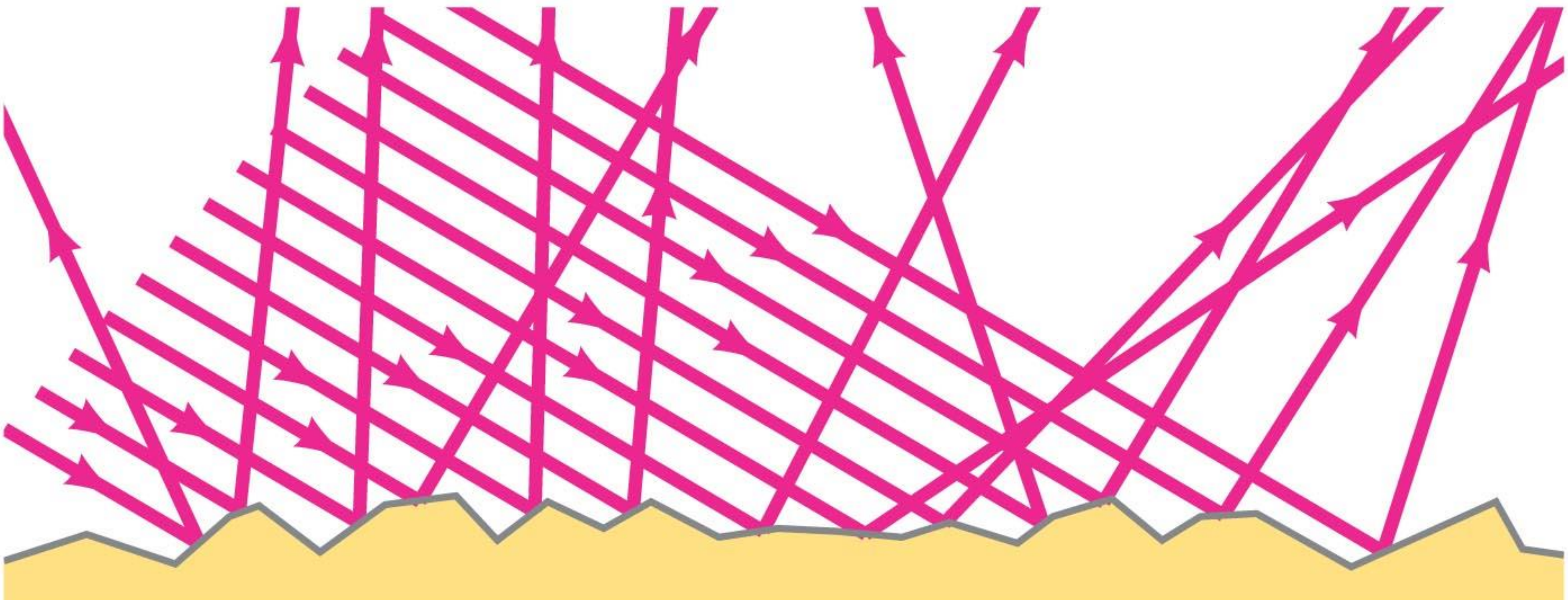
Law of reflection: the angle of reflection (that the ray makes with the normal to a surface) equals the angle of incidence.





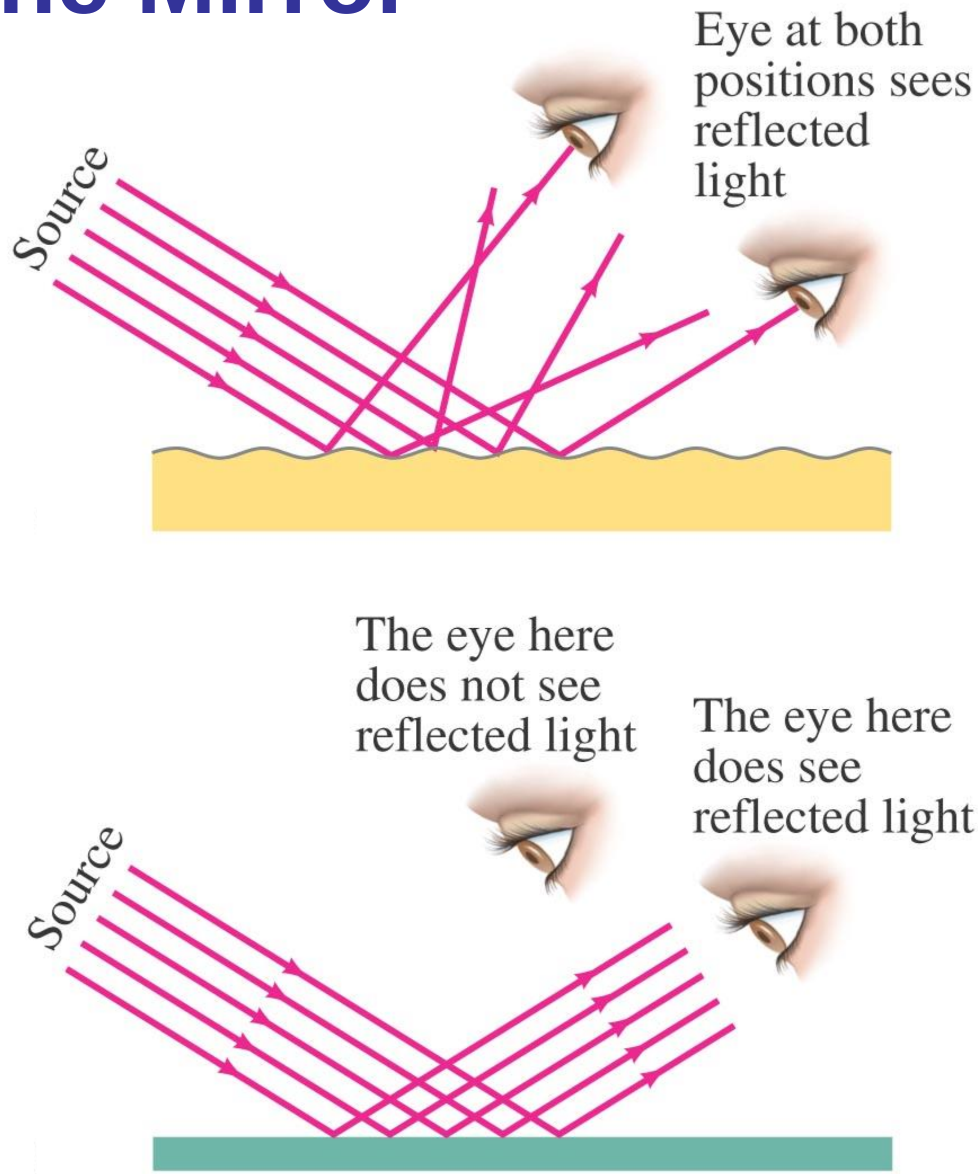
32-2 Reflection; Image Formation by a Plane Mirror

When light reflects from a rough surface, the law of reflection still holds, but the angle of incidence varies. This is called diffuse reflection.



32-2 Reflection; Image Formation by a Plane Mirror

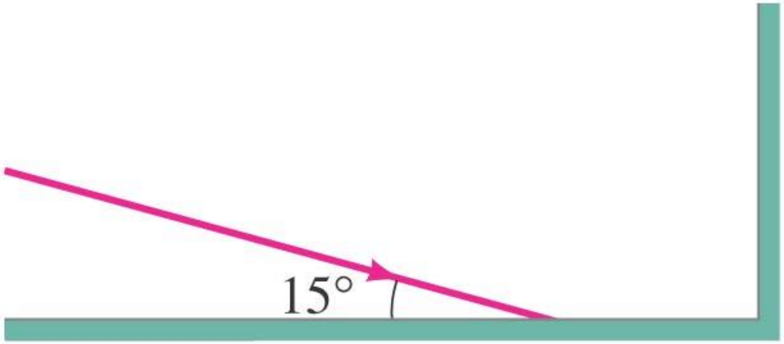
With diffuse reflection, your eye sees reflected light at all angles. With specular reflection (from a mirror), your eye must be in the correct position.

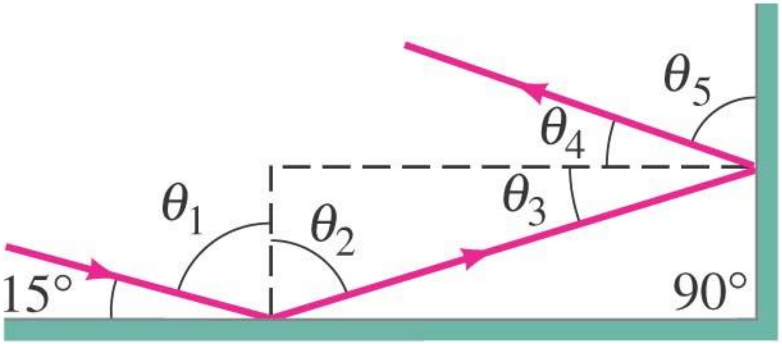


32-2 Reflection; Image Formation by a Plane Mirror

Example 32-1: Reflection from flat mirrors.

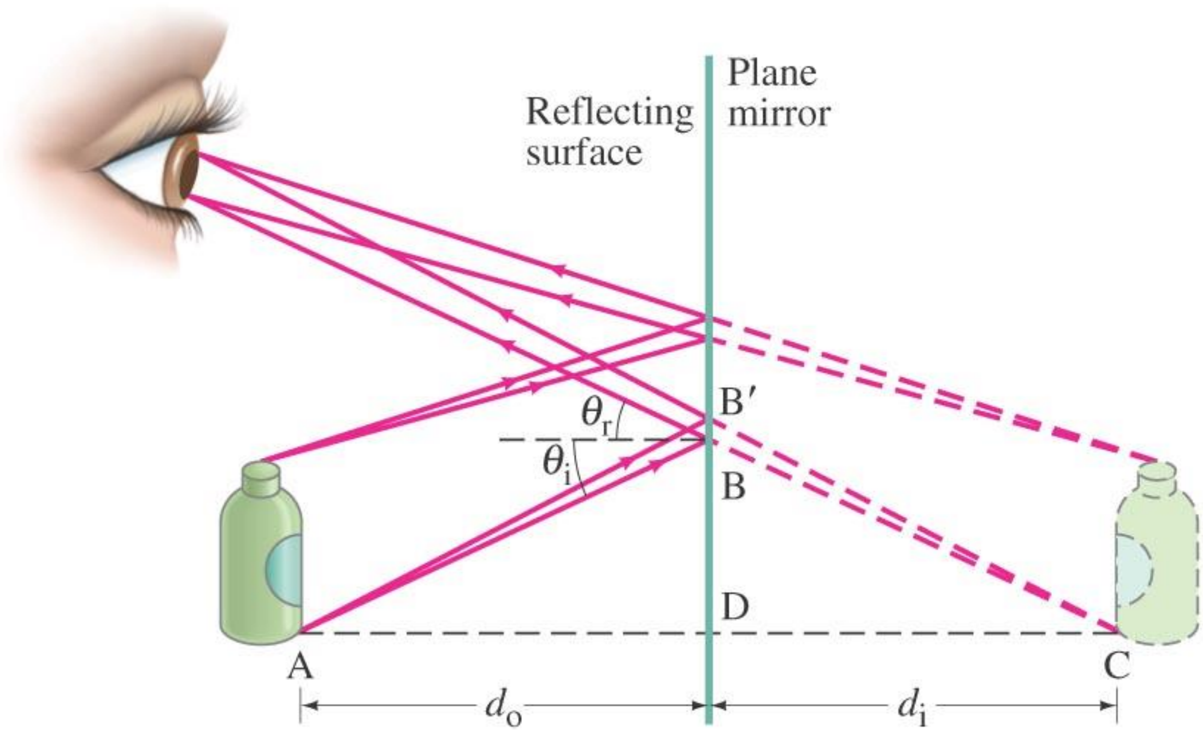
Two flat mirrors are perpendicular to each other. An incoming beam of light makes an angle of 15° with the first mirror as shown. What angle will the outgoing beam make with the second mirror?





32-2 Reflection; Image Formation by a Plane Mirror

What you see when you look into a plane (flat) mirror is an image, which appears to be behind the mirror.



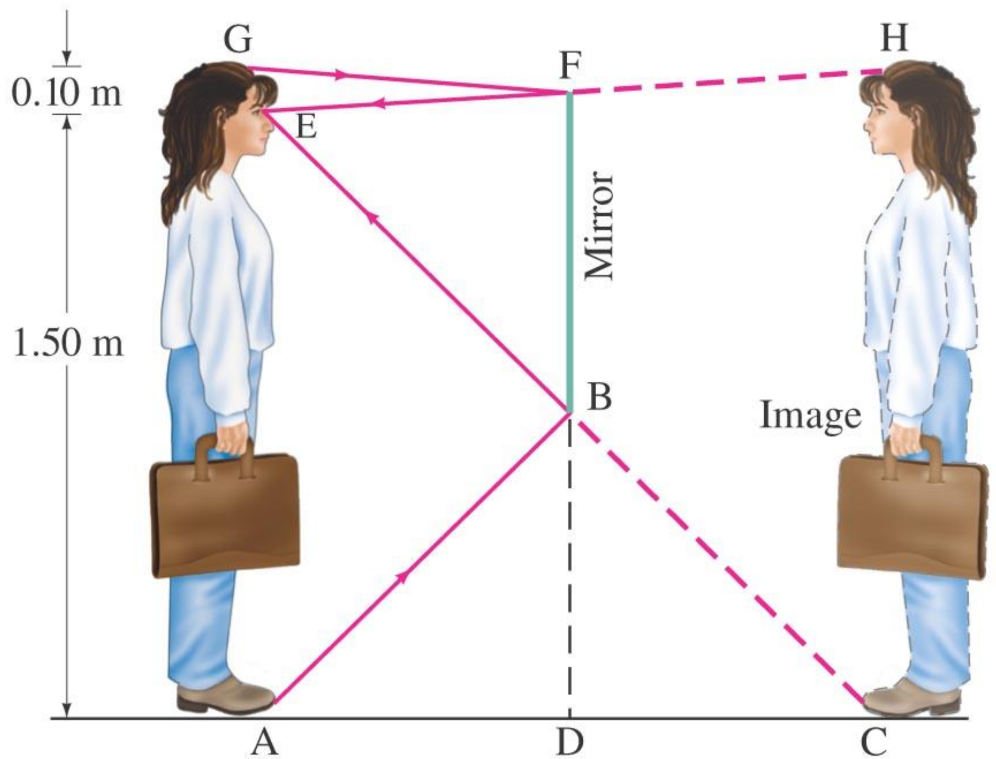
32-2 Reflection; Image Formation by a Plane Mirror

This is called a virtual image, as the light does not go through it. The distance of the image from the mirror is equal to the distance of the object from the mirror.

32-2 Reflection; Image Formation by a Plane Mirror

Example 32-2: How tall must a full-length mirror be?

A woman 1.60 m tall stands in front of a vertical plane mirror. What is the minimum height of the mirror, and how close must its lower edge be to the floor, if she is to be able to see her whole body? Assume her eyes are 10 cm below the top of her head.



32-2 Reflection; Image Formation by a Plane Mirror

Solution: At the minimum height, light from her feet strikes the bottom edge of the mirror and reflects into her eyes; light from the top of her head strikes the top edge of the mirror and reflects into her eyes. Geometry then shows that the mirror must be 80 cm high, with its bottom 75 cm off the floor.

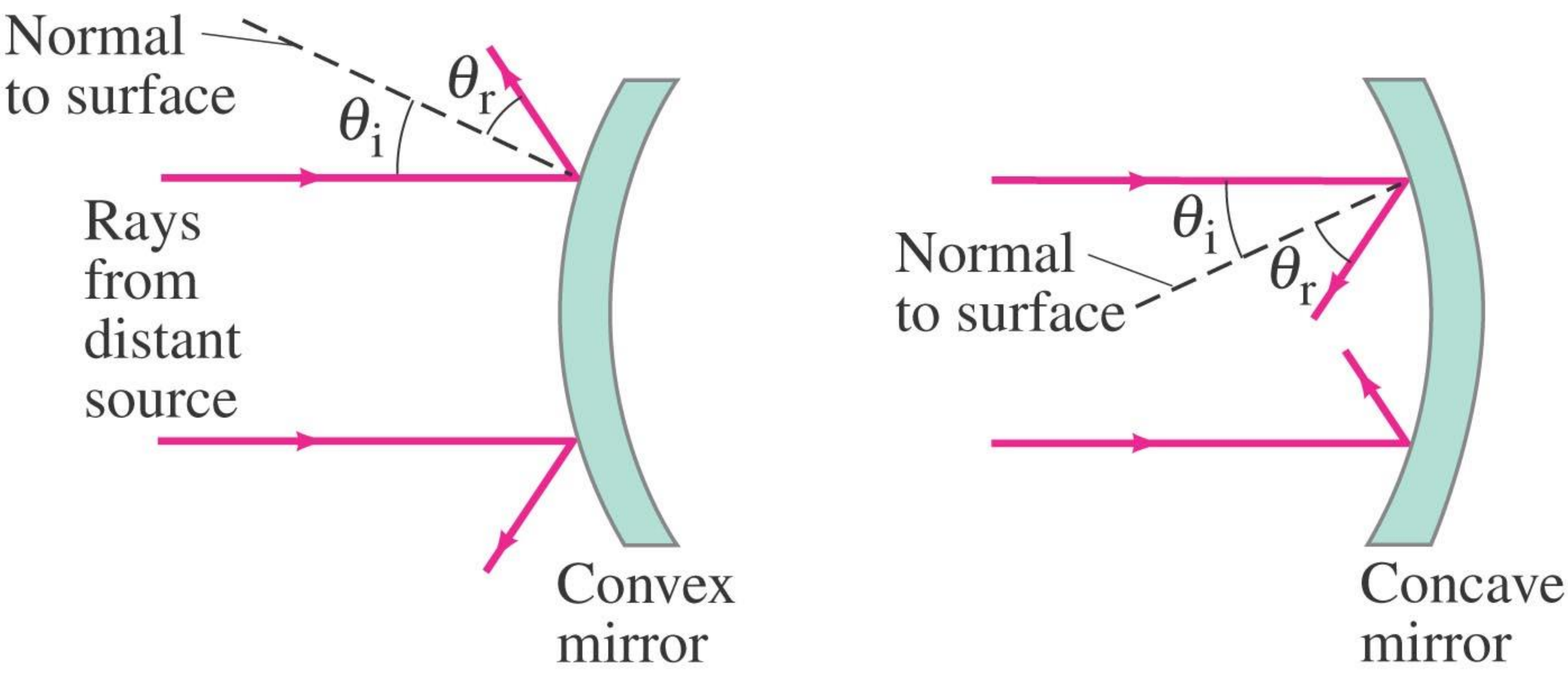
32-2 Reflection; Image Formation by a Plane Mirror

Conceptual Example 32-3: Is the photo upside down?

Close examination of the photograph on the first page of this Chapter reveals that in the top portion, the image of the Sun is seen clearly, whereas in the lower portion, the image of the Sun is partially blocked by the tree branches. Show why the reflection is not the same as the real scene by drawing a sketch of this situation, showing the Sun, the camera, the branch, and two rays going from the Sun to the camera (one direct and one reflected). Is the photograph right side up?

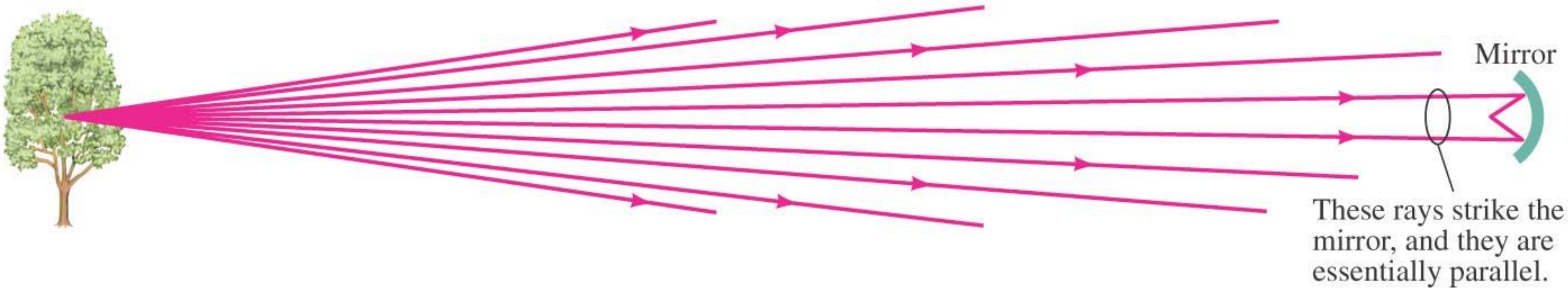
32-3 Formation of Images by Spherical Mirrors

Spherical mirrors are shaped like sections of a sphere, and may be reflective on either the inside (concave) or outside (convex).



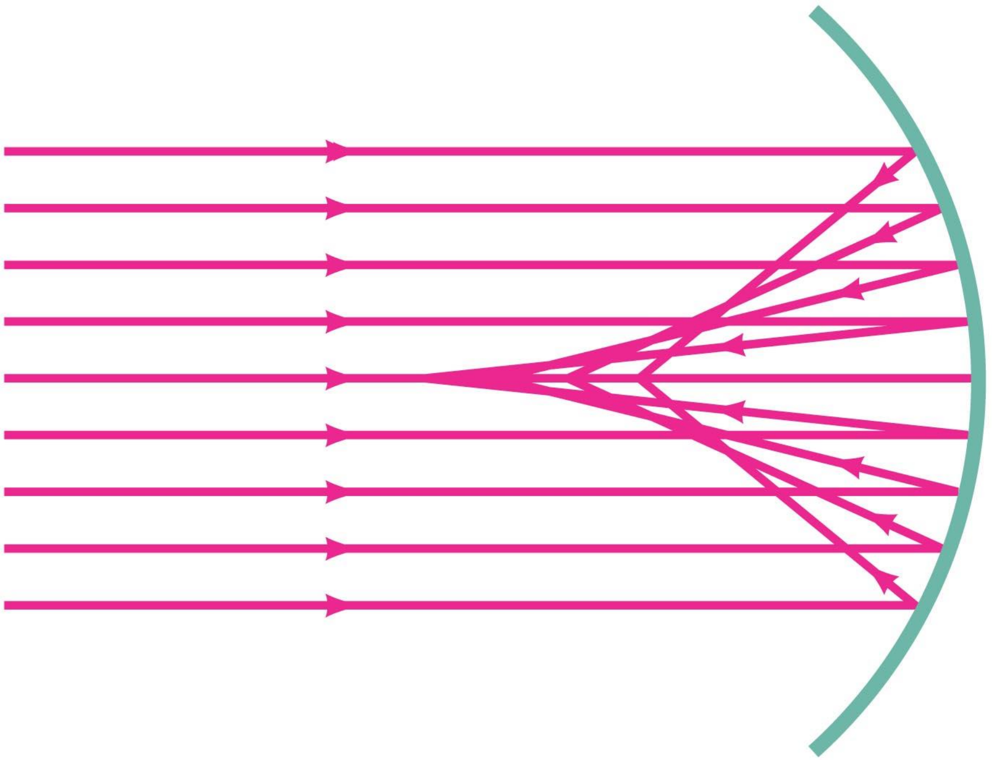
32-3 Formation of Images by Spherical Mirrors

Rays coming from a faraway object are effectively parallel.



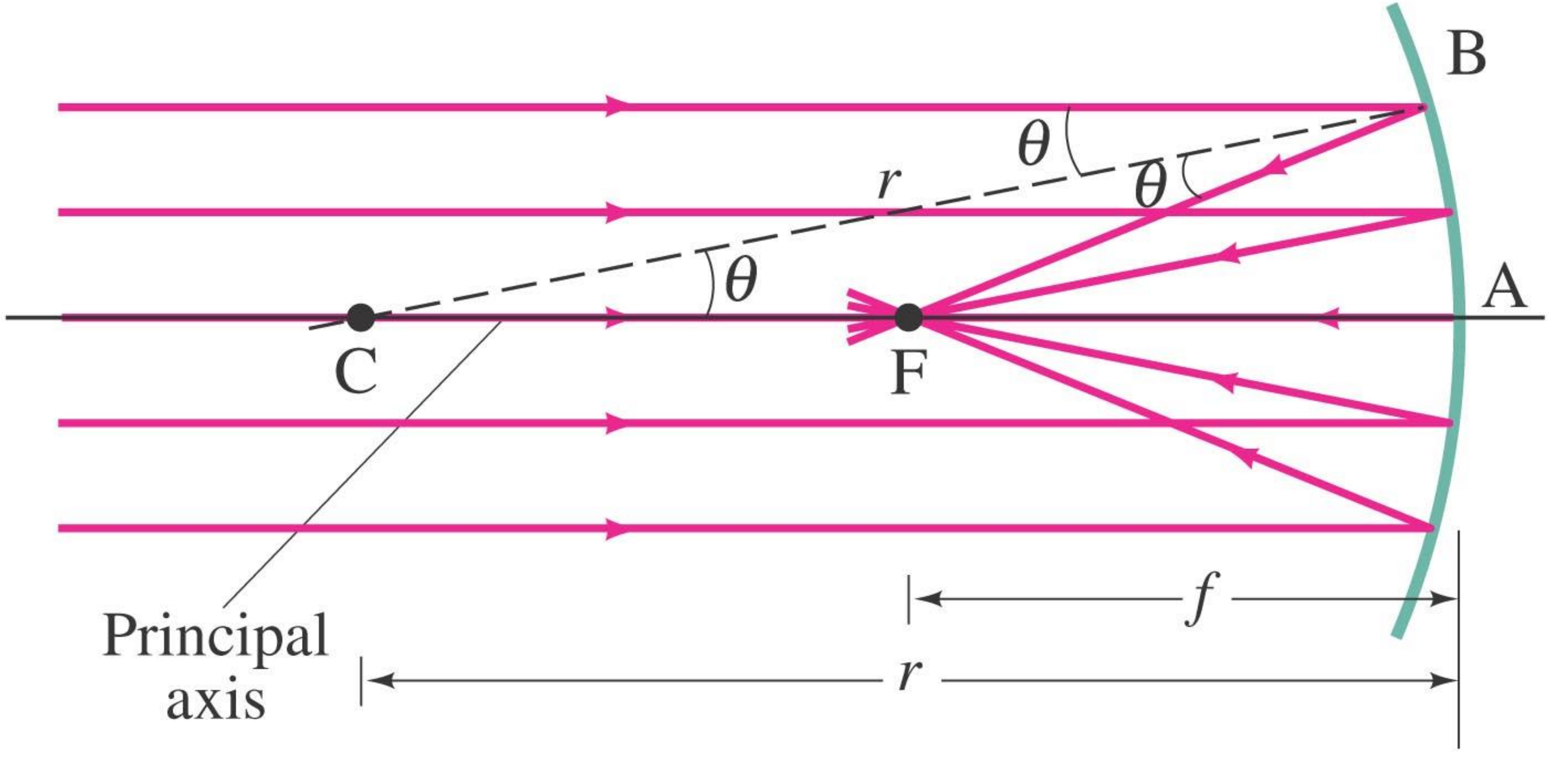
32-3 Formation of Images by Spherical Mirrors

Parallel rays striking a spherical mirror do not all converge at exactly the same place if the curvature of the mirror is large; this is called spherical aberration.



32-3 Formation of Images by Spherical Mirrors

If the curvature is small, the focus is much more precise; the focal point is where the rays converge.



32-3 Formation of Images by Spherical Mirrors

Using geometry, we find that the focal length is half the radius of curvature:

$$f = \frac{r}{2}. \qquad \text{[spherical mirror]}$$

Spherical aberration can be avoided by using a parabolic reflector; these are more difficult and expensive to make, and so are used only when necessary, such as in research telescopes.

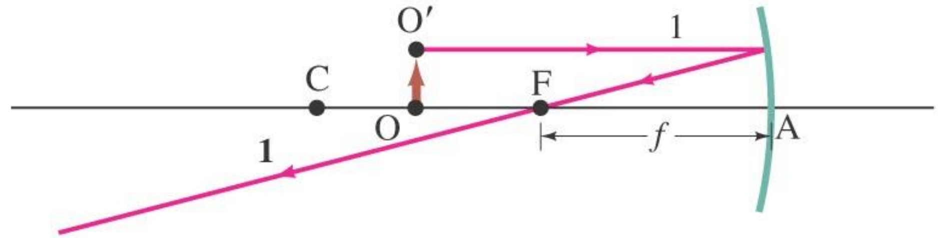
32-3 Formation of Images by Spherical Mirrors

We use ray diagrams to determine where an image will be. For mirrors, we use three key rays, all of which begin on the object:

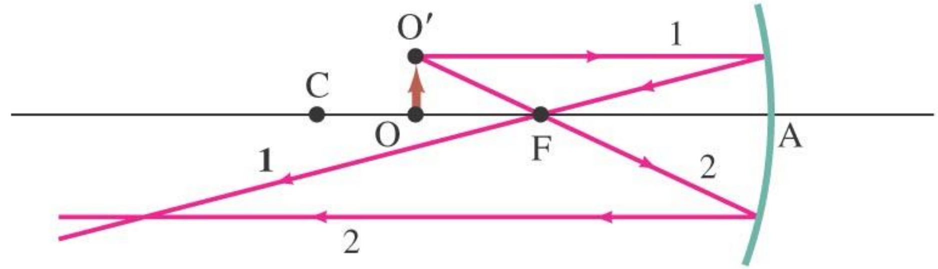
1. A ray parallel to the axis; after reflection it passes through the focal point.
2. A ray through the focal point; after reflection it is parallel to the axis.
3. A ray perpendicular to the mirror; it reflects back on itself.

32-3 Formation of Images by Spherical Mirrors

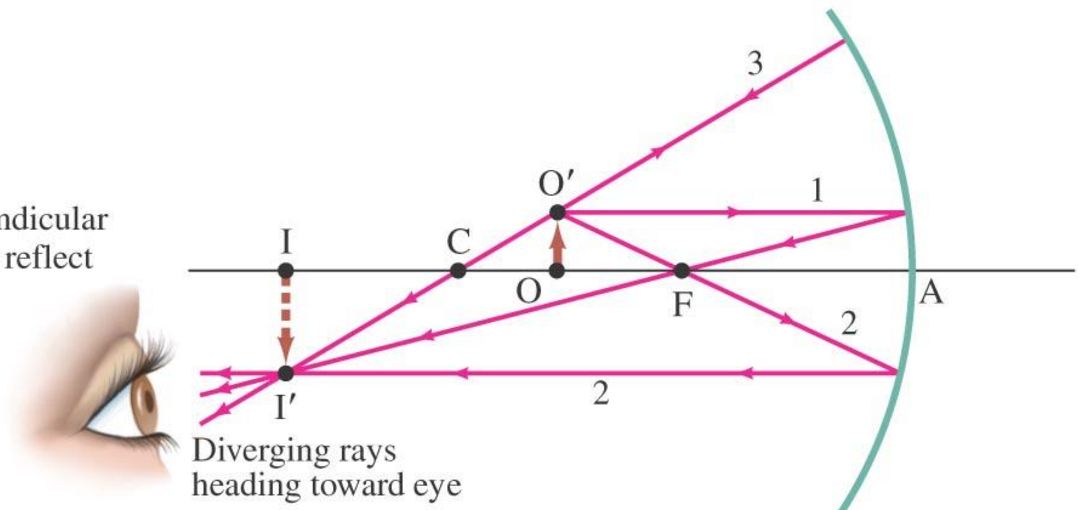
Ray 1 goes out from O′ parallel to the axis and reflects through F.



Ray 2 goes through F and then reflects back parallel to the axis.



Ray 3 is chosen perpendicular to mirror, and so must reflect back on itself and go through C (center of curvature).



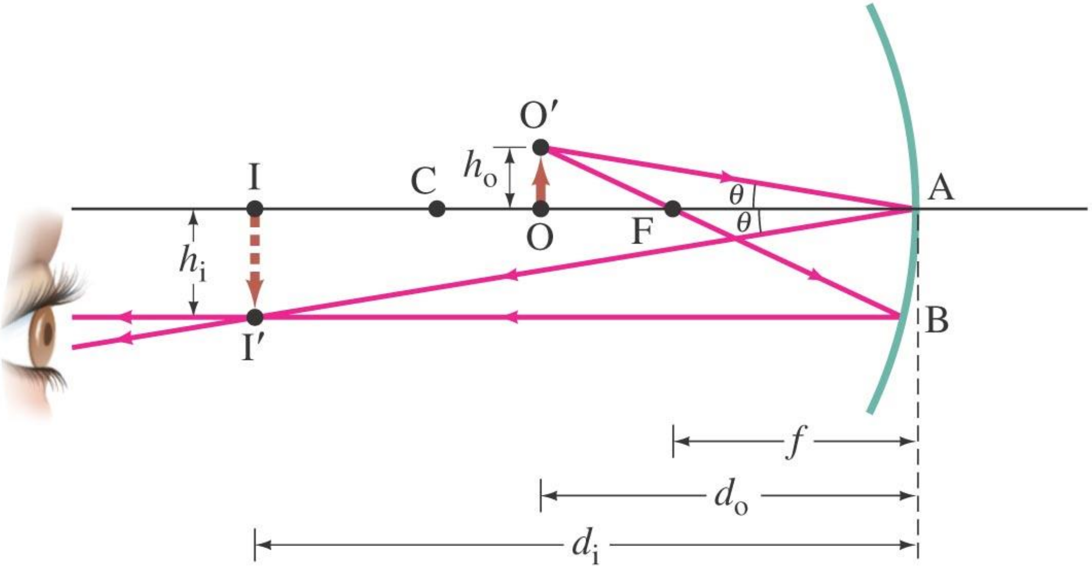
32-3 Formation of Images by Spherical Mirrors

The intersection of these three rays gives the position of the image of that point on the object. To get a full image, we can do the same with other points (two points suffice for may purposes).

32-3 Formation of Images by Spherical Mirrors

Geometrically, we can derive an equation that relates the object distance, image distance, and focal length of the mirror:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}.$$



32-3 Formation of Images by Spherical Mirrors

We can also find the magnification (ratio of image height to object height):

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}.$$

The negative sign indicates that the image is inverted. This object is between the center of curvature and the focal point, and its image is larger, inverted, and real.

32-3 Formation of Images by Spherical Mirrors

Example 32-4: Image in a concave mirror.

A 1.50-cm-high diamond ring is placed 20.0 cm from a concave mirror with radius of curvature 30.0 cm. Determine (a) the position of the image, and (b) its size.

Solution:

(a). Using the mirror equation,

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}.$$

we find d_i = 60.0 cm.

(b). Using the magnification equation,

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}.$$

we find M = -3.00 and h_i = - 4.5 cm.

Calculation on mirrors

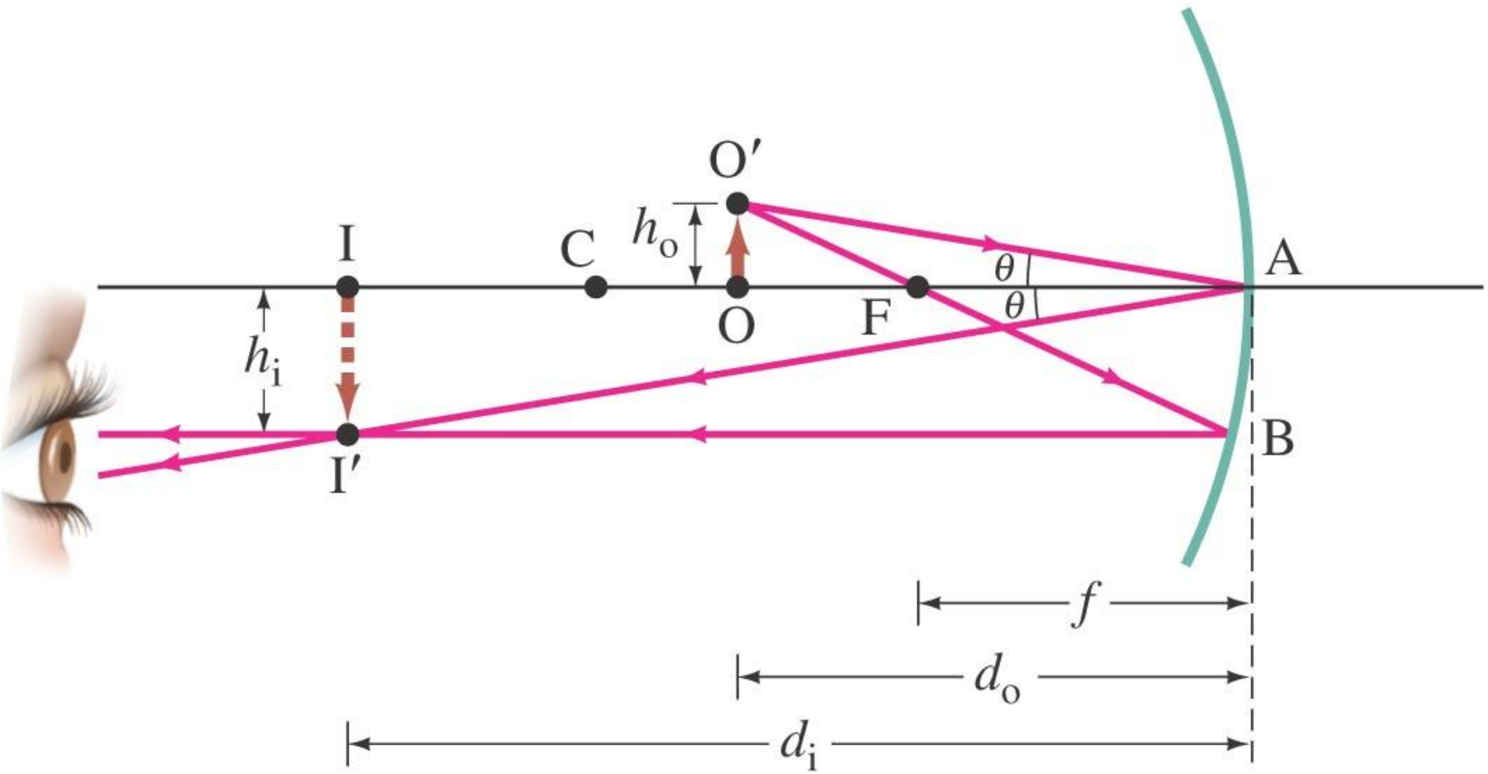
- Two mirrors M_1 & M_2 make an angle of 120^o with each other. A ray is incident on mirror M1 at an angle of 65^o to the normal. Find the direction of the ray after it is reflected from mirror M_2 is 120^0
- A certain spherical mirror has a focal length of + 10 cm. Locate and describe the image for object distances of (a) 25.0 cm (b) 10.0 cm (c) 5.0 cm

  Ans (a) q =16.7 cm , M = -0.67 (b) q = α , (c) q = - 10 cm, M = 2.0
- An object 1.5 m high is located 3.0 m from an anti-shoplifting mirror of focal length –25 cm. Find (a) position of the image (b) the magnification (c) if the object is 5.0 cm from the mirror, what is the position of the image and its magnification?
- Ans (a) q = -0.23 m (b) M = 0.077 (c)

32-3 Formation of Images by Spherical Mirrors

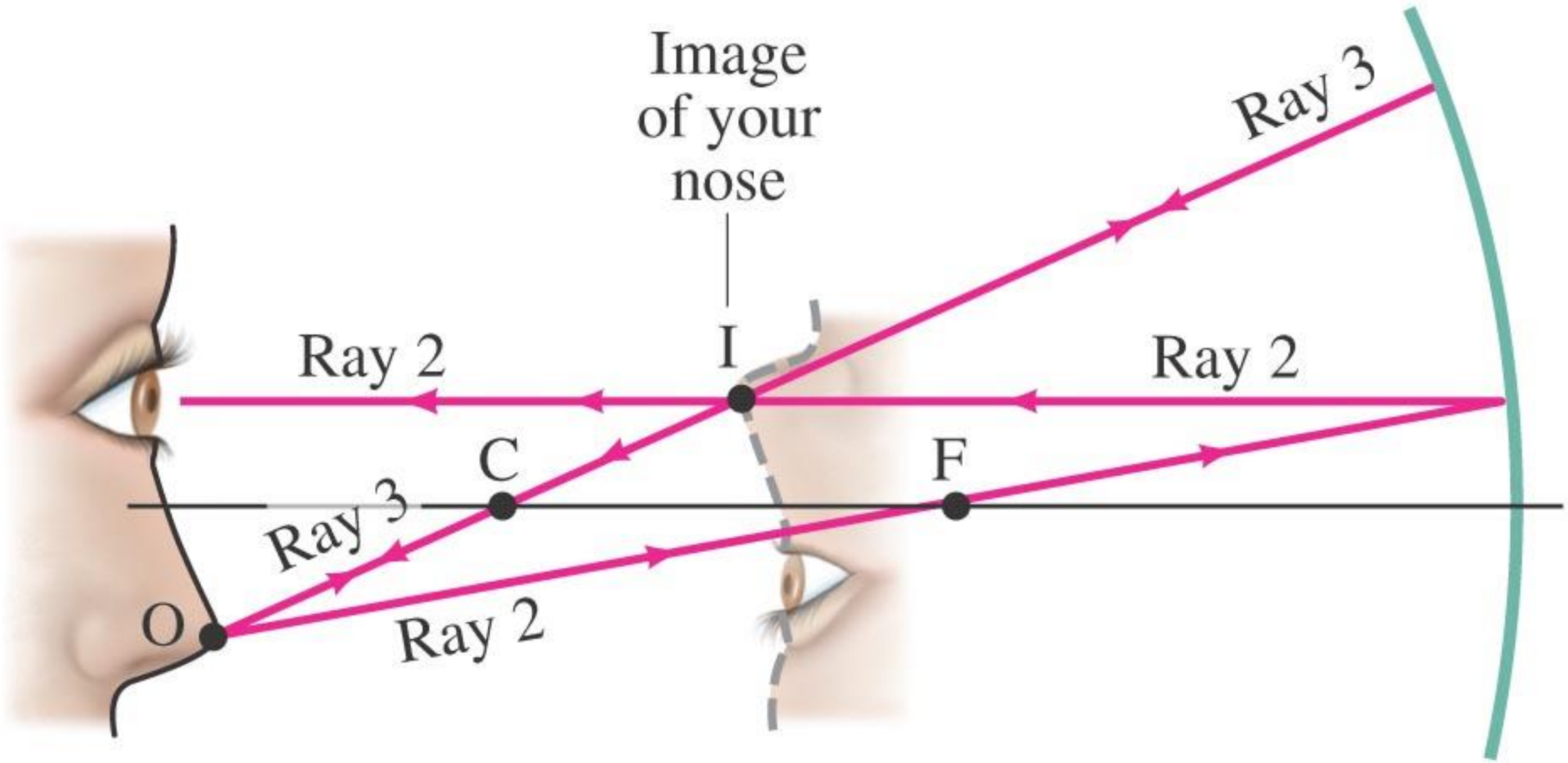
Conceptual Example 32-5: Reversible rays.

If the object in this figure is placed where the image is, where will the new image be?



32-3 Formation of Images by Spherical Mirrors

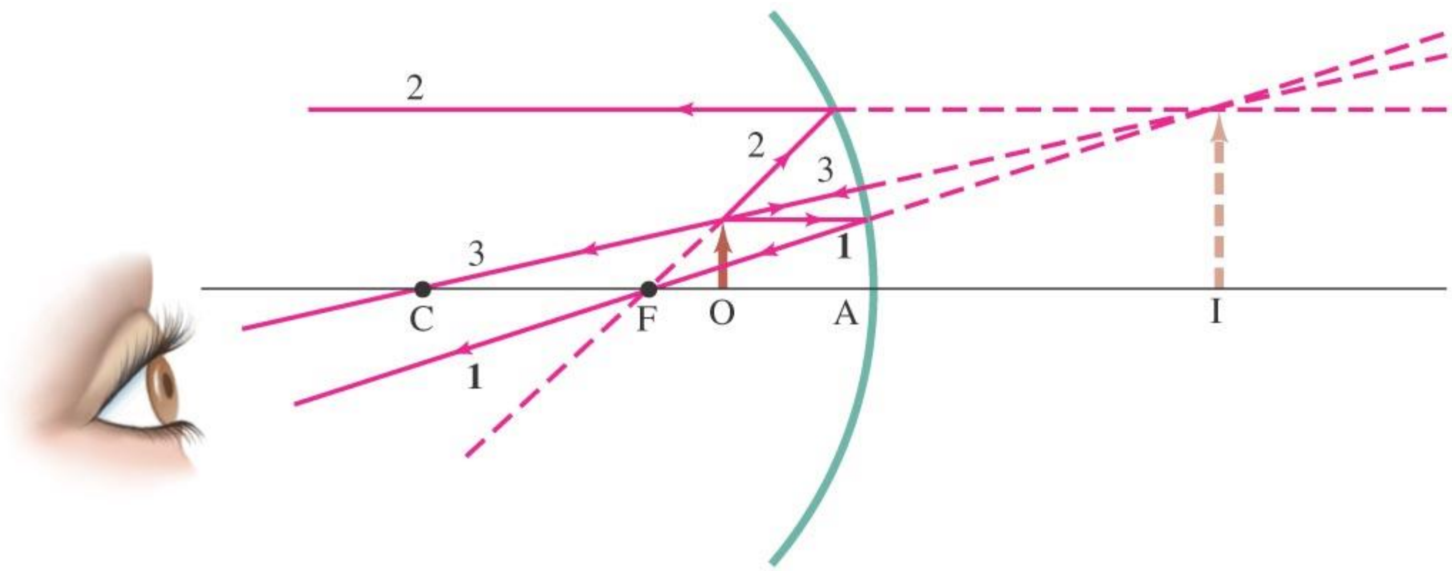
If an object is outside the center of curvature of a concave mirror, its image will be inverted, smaller, and real.



32-3 Formation of Images by Spherical Mirrors

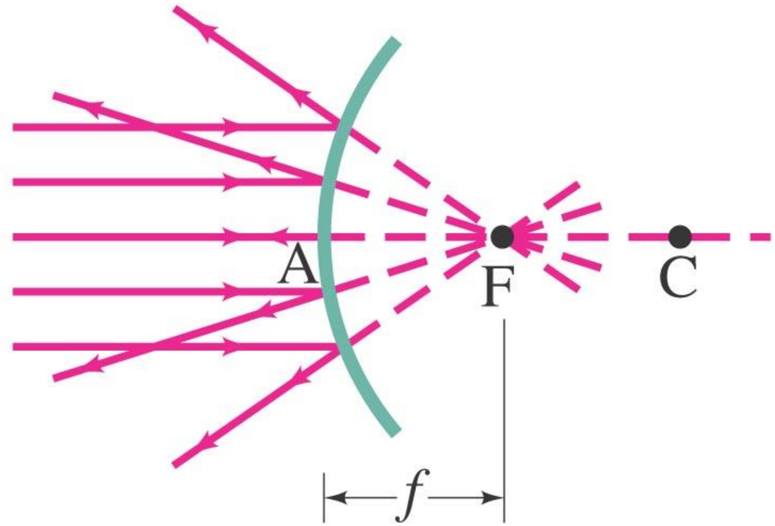
Example 32-6: Object closer to concave mirror.

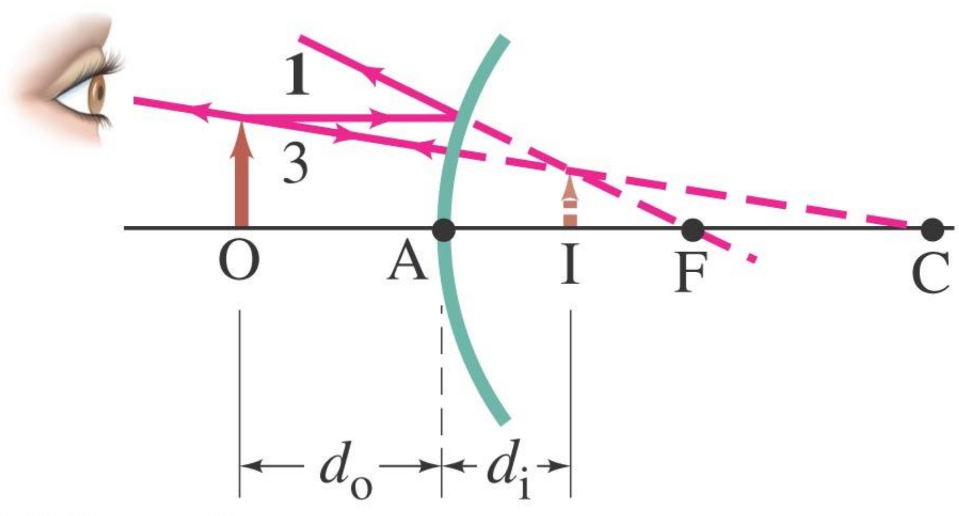
A 1.00-cm-high object is placed 10.0 cm from a concave mirror whose radius of curvature is 30.0 cm. (a) Draw a ray diagram to locate (approximately) the position of the image. (b) Determine the position of the image and the magnification analytically.



32-3 Formation of Images by Spherical Mirrors

For a convex mirror, the image is always virtual, upright, and smaller.





32-3 Formation of Images by Spherical Mirrors

Problem Solving: Spherical Mirrors

1. Draw a ray diagram; the image is where the rays intersect.
2. Apply the mirror and magnification equations.
3. Sign conventions: if the object, image, or focal point is on the reflective side of the mirror, its distance is positive, and negative otherwise. Magnification is positive if image is upright, negative otherwise.
4. Check that your solution agrees with the ray diagram.

32-3 Formation of Images by Spherical Mirrors

Example 32-7: Convex rearview mirror.

An external rearview car mirror is convex with a radius of curvature of 16.0 m. Determine the location of the image and its magnification for an object 10.0 m from the mirror.

32-4 Index of Refraction

In general, light slows somewhat when traveling through a medium. The index of refraction of the medium is the ratio of the speed of light in vacuum to the speed of light in the medium:

$$n = \frac{c}{v}.$$

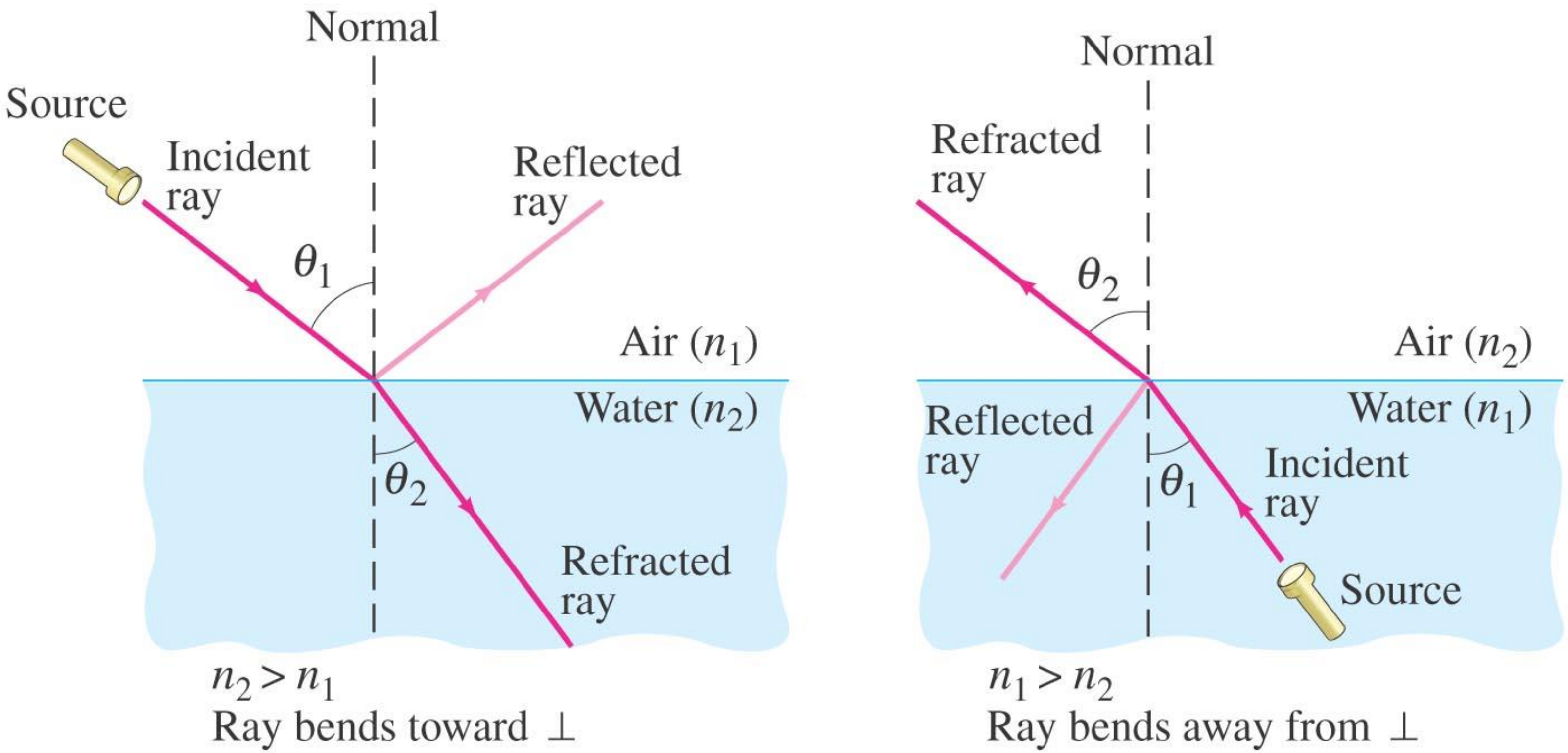
TABLE 32–1 Indices of Refraction[†]

Material	$n = \frac{c}{v}$
Vacuum	1.0000
Air (at STP)	1.0003
Water	1.33
Ethyl alcohol	1.36
Glass	
Fused quartz	1.46
Crown glass	1.52
Light flin	.58
Lucite or Plexiglas	1.51
Sodium chloride	1.53
Diamond	2.42

[†] $\lambda = 589$ nm.

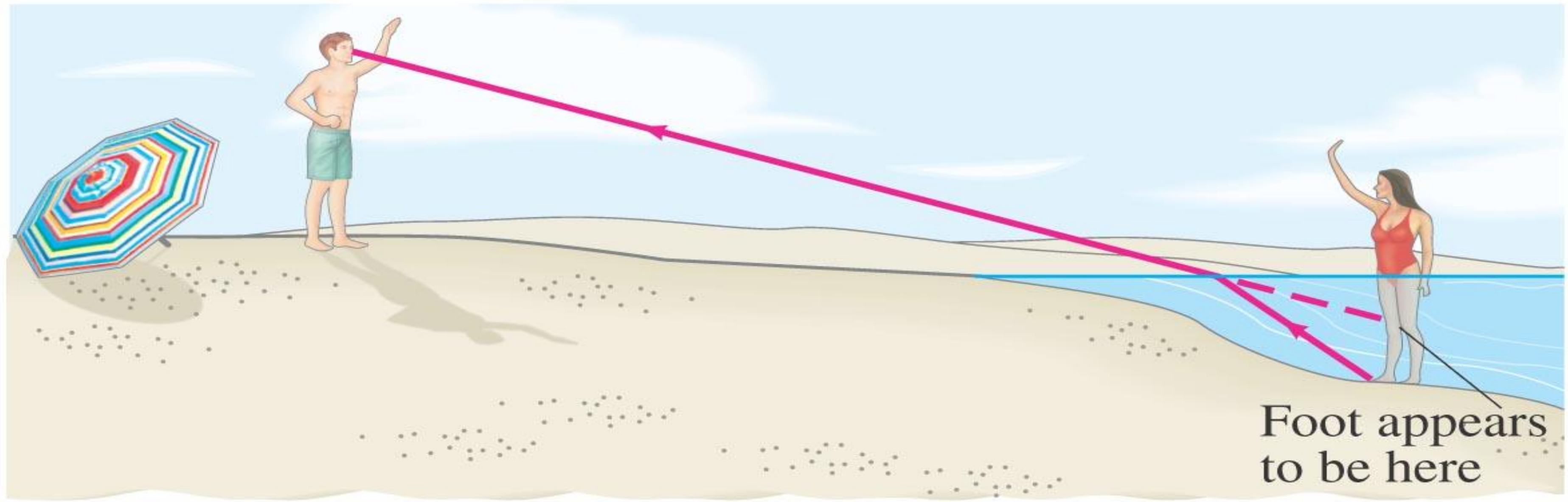
32-5 Refraction: Snell's Law

Light changes direction when crossing a boundary from one medium to another. This is called refraction, and the angle the outgoing ray makes with the normal is called the angle of refraction.



32-5 Refraction: Snell's Law

Refraction is what makes objects half-submerged in water look odd (optical illusions)



A person standing in waist-deep waters appears to have shortened legs. As shown above, the rays leaving the person's foot are bent at the surface

32-5 Refraction: Snell's Law

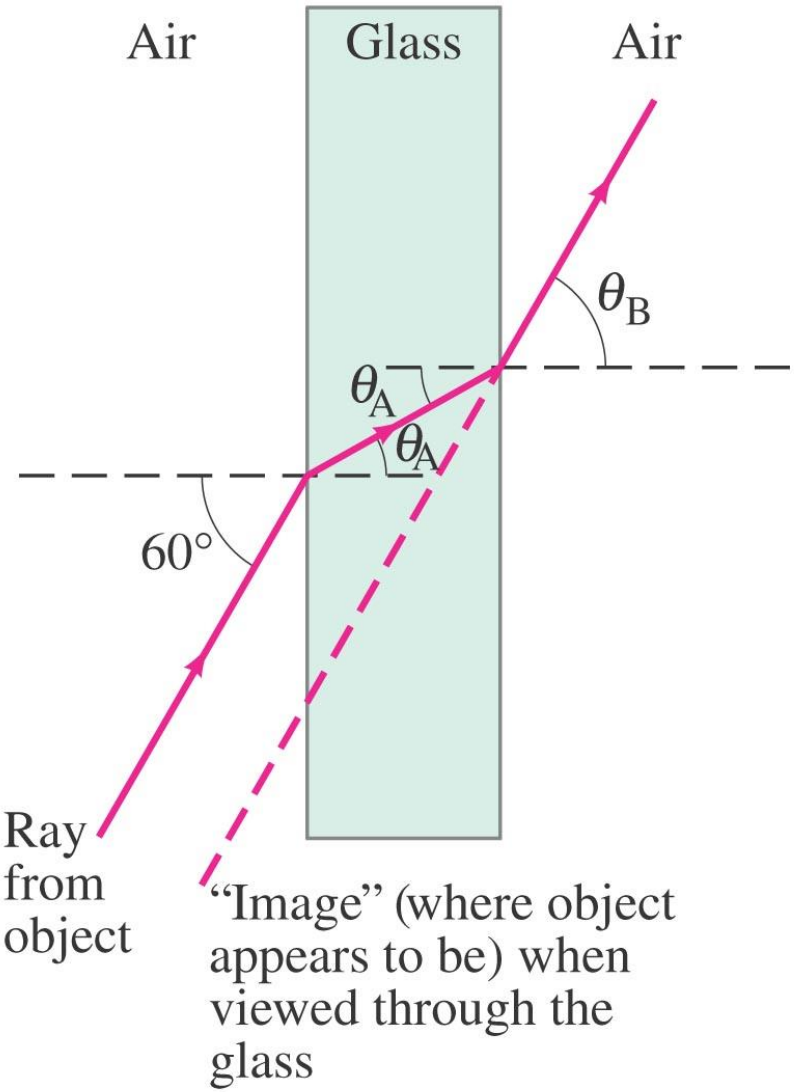
The angle of refraction depends on the indices of refraction, and is given by Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 .$$

32-5 Refraction: Snell's Law

Example 32-8: Refraction through flat glass.

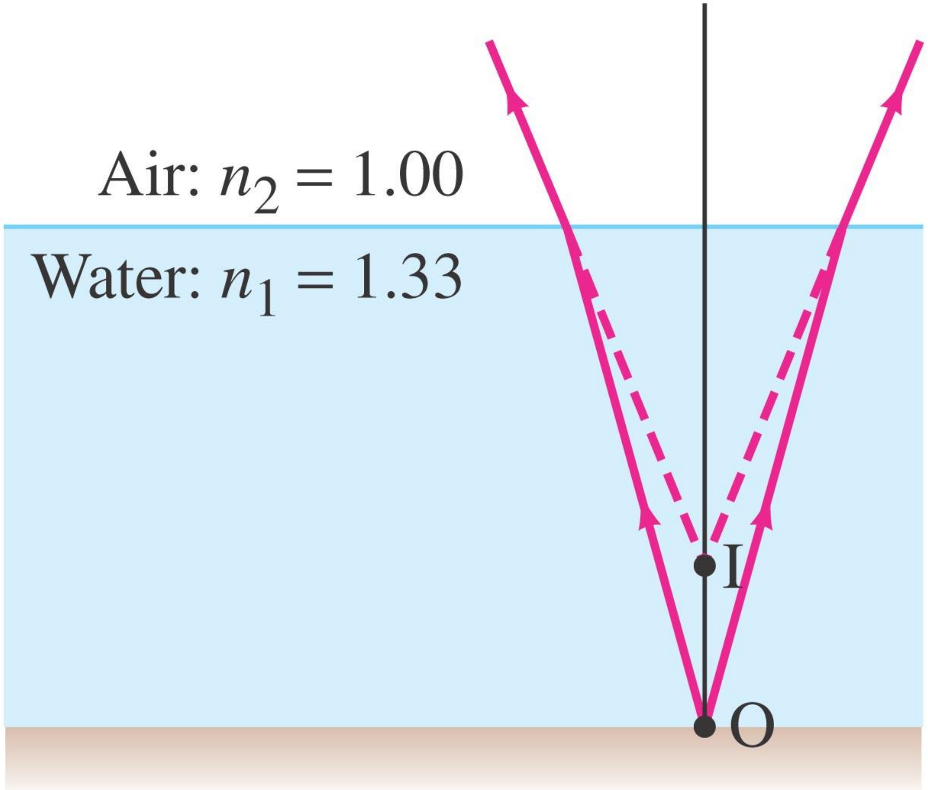
Light traveling in air strikes a flat piece of uniformly thick glass at an incident angle of 60°, as shown. If the index of refraction of the glass is 1.50, (a) what is the angle of refraction θ_A in the glass; (b) what is the angle θ_B at which the ray emerges from the glass?



32-8 Refraction at a Spherical Surface

Example 32-12: Apparent depth II.

A person looks vertically down into a 1.0-m-deep pool. How deep does the water appear to be?



32-5 Refraction: Snell's Law

Example 32-9: Apparent depth of a pool.

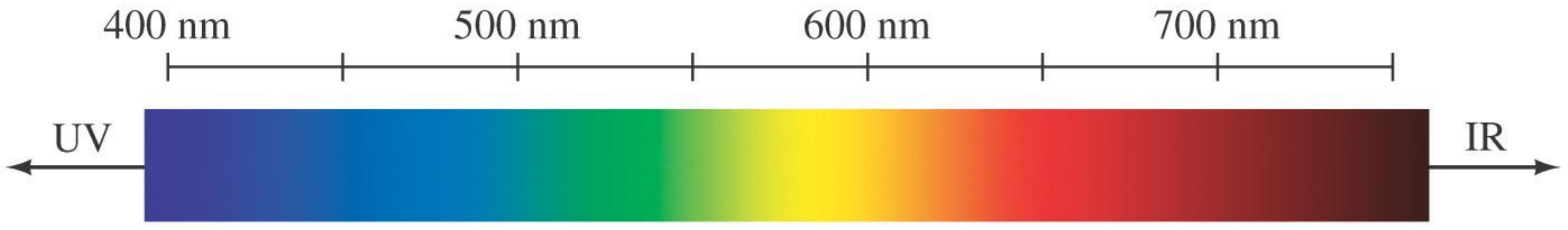
A swimmer has dropped her goggles to the bottom of a pool at the shallow end, marked as 1.0 m deep. But the goggles don't look that deep. Why? How deep do the goggles appear to be when you look straight down into the water?

32-6 Visible Spectrum and Dispersion

An obvious property of visible light is its color. Color can be related to the wavelengths or frequencies of light.

Visible light is the light to which our eyes are sensitive, has wavelengths in air in the range of 400nm to 700nm. This is called visible spectrum.

The visible spectrum contains the full range of wavelengths of light that are visible to the human eye. Human eyes are not sensitive to UV and IR.

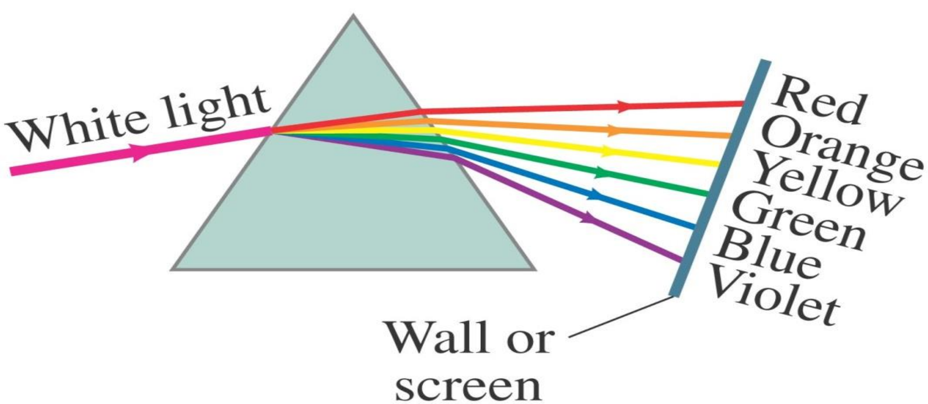


32-6 Visible Spectrum and Dispersion

The index of refraction of many transparent materials, such as glass and water, varies slightly with wavelength. This is how prisms and water droplets create rainbows from sunlight.

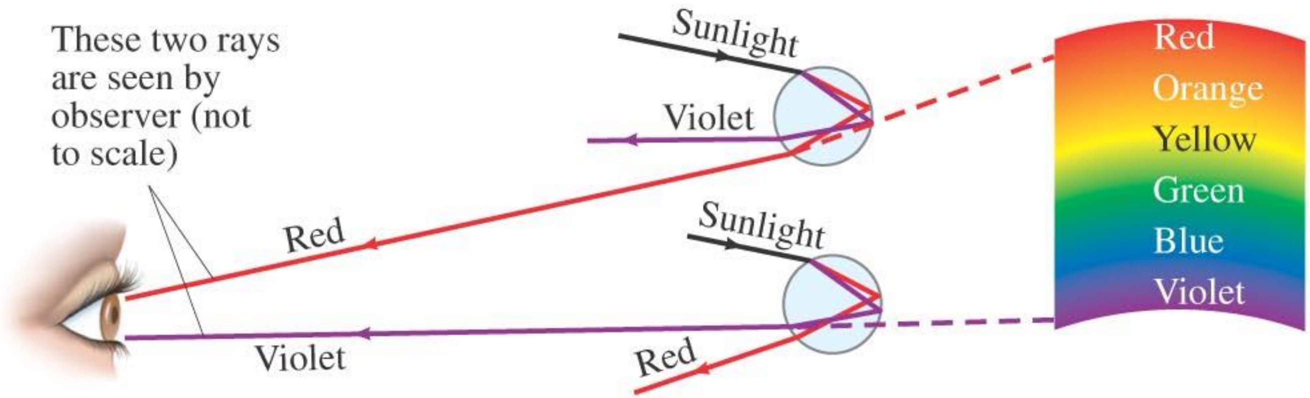
White light is a mixture of all visible wavelengths, and when incident on a prism, the different wavelengths are bent to varying degrees.

Since the index of refraction is greater for the shorter wavelengths, violet light is bent the most and red the least.



32-6 Visible Spectrum and Dispersion

This spreading of light into the full spectrum is called dispersion.



32-6 Visible Spectrum and Dispersion

Conceptual Example 32-10: Observed color of light under water.

We said that color depends on wavelength. For example, for an object emitting 650 nm light in air, we see red. But this is true only in air. If we observe this same object when under water, it still looks red. But the wavelength in water λ_n is 650 nm/1.33 = 489 nm. Light with wavelength 489 nm would appear blue in air. Can you explain why the light appears red rather than blue when observed under water?

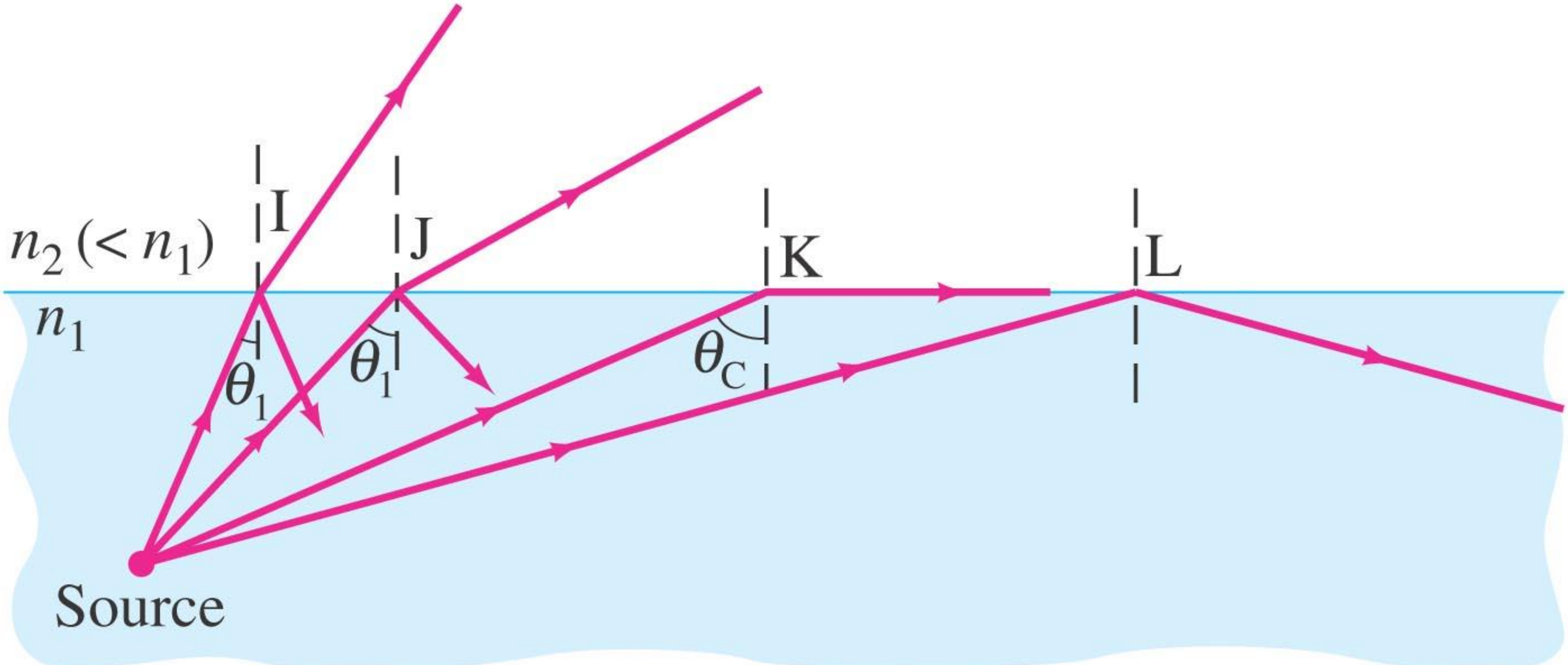
32-7 Total Internal Reflection; Fiber Optics

If light passes into a medium with a smaller index of refraction, the angle of refraction is larger. There is an angle of incidence for which the angle of refraction will be 90°; this is called the critical angle:

$$\sin\theta_C = \frac{n_2}{n_1}\sin 90^\circ = \frac{n_2}{n_1}.$$

32-7 Total Internal Reflection; Fiber Optics

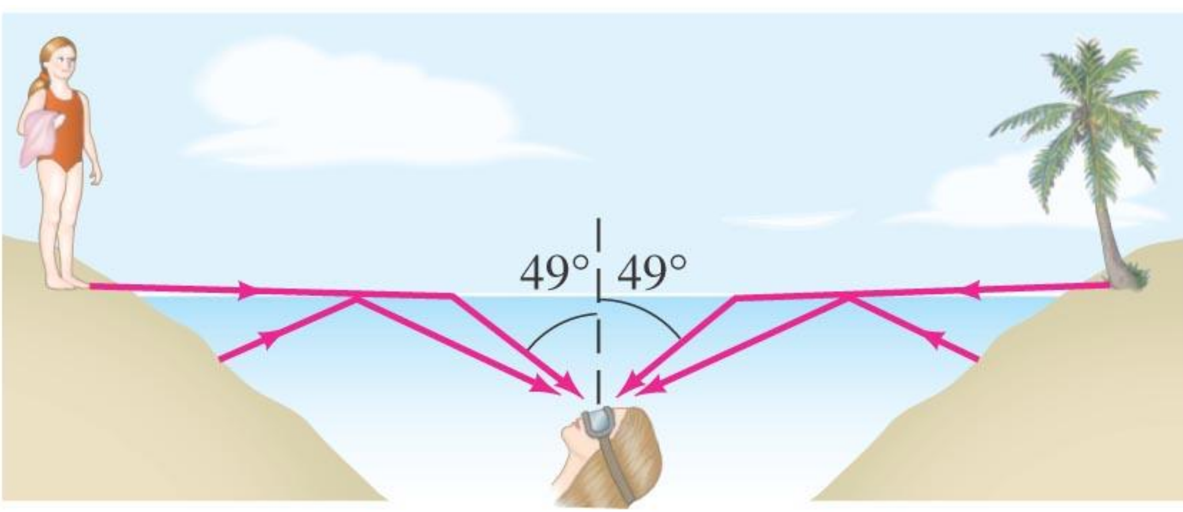
If the angle of incidence is larger than this, no transmission occurs. This is called total internal reflection.

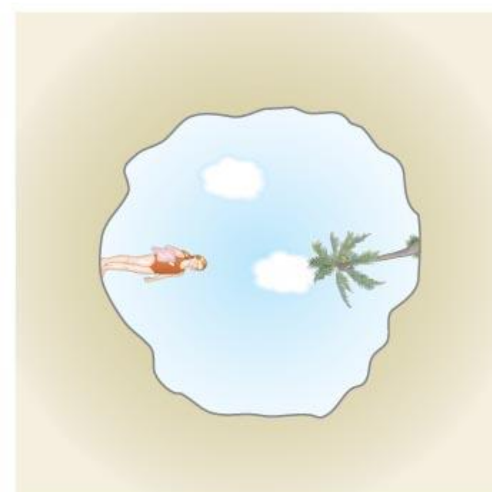


32-7 Total Internal Reflection; Fiber Optics

Conceptual Example 32-11: View up from under water.

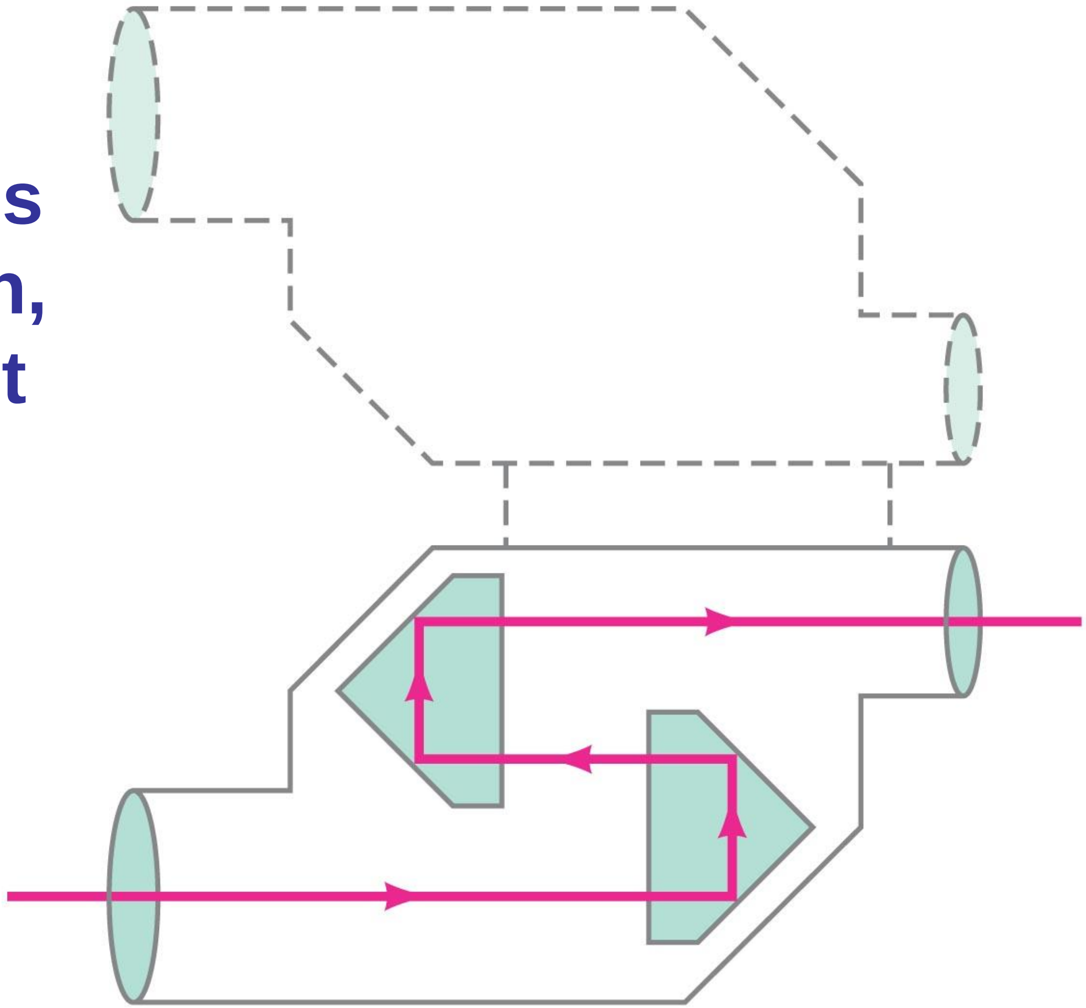
Describe what a person would see who looked up at the world from beneath the perfectly smooth surface of a lake or swimming pool.





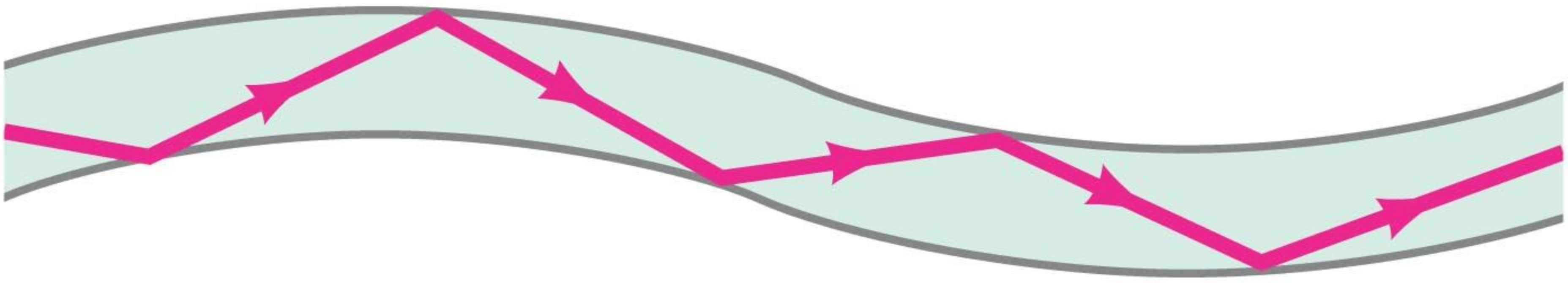
32-7 Total Internal Reflection; Fiber Optics

Binoculars often use total internal reflection; this gives true 100% reflection, which even the best mirror cannot do.



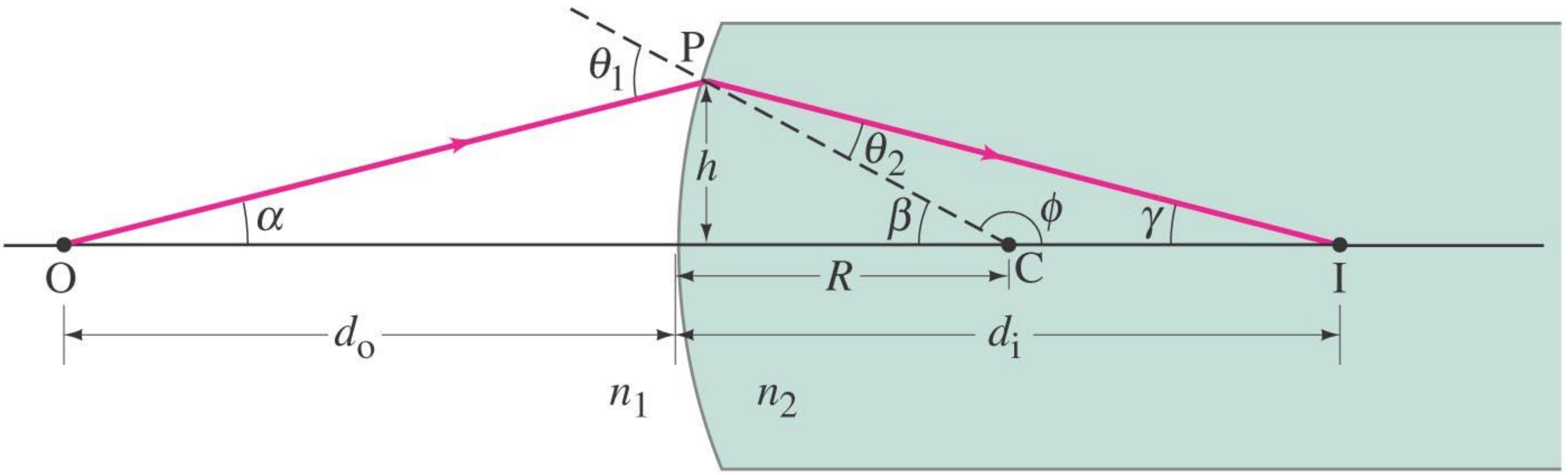
32-7 Total Internal Reflection; Fiber Optics

Optical fibers also depend on total internal reflection; they are therefore able to transmit light signals with very small losses.



32-8 Refraction at a Spherical Surface

Rays from a single point will be focused by a convex spherical interface with a medium of larger index of refraction to a single point, as long as the angles are not too large.



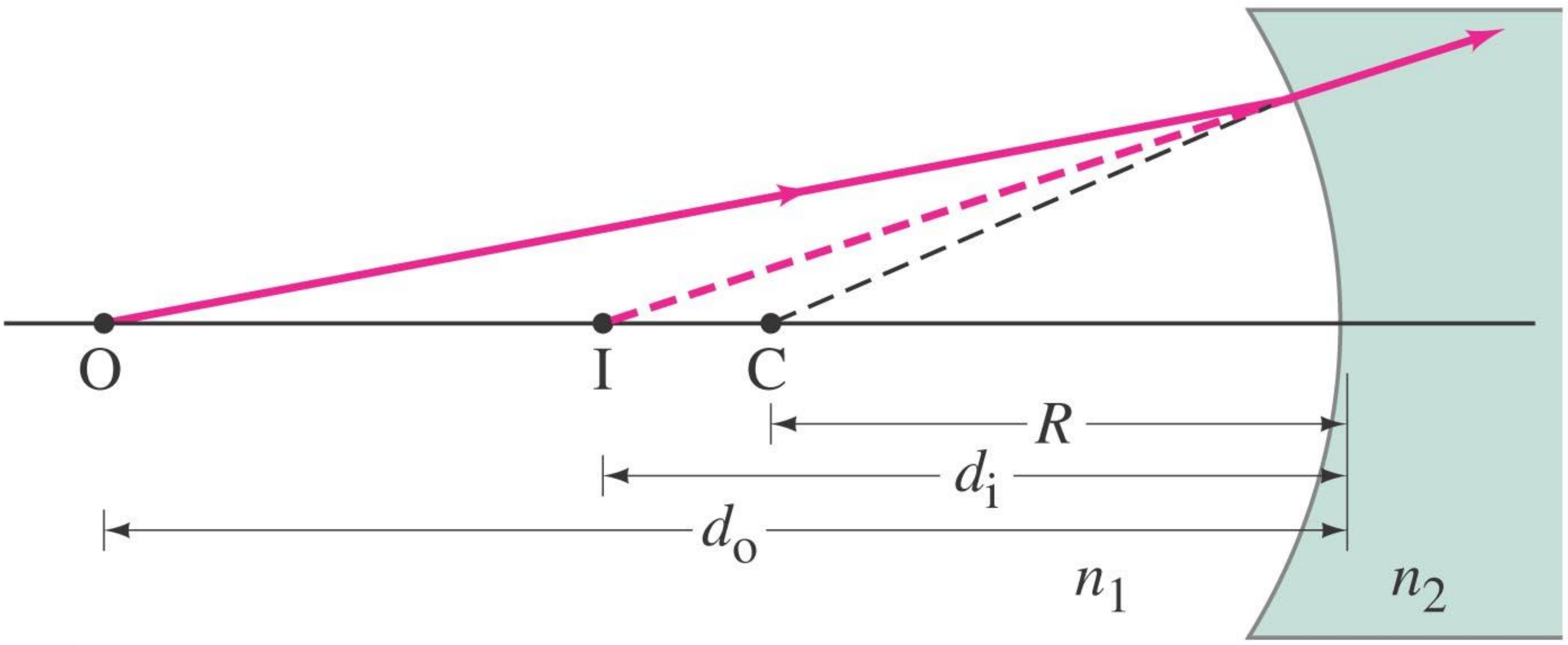
32-8 Refraction at a Spherical Surface

Geometry gives the relationship between the indices of refraction, the object distance, the image distance, and the radius of curvature:

$$\frac{n_1}{d_o} + \frac{n_2}{d_i} = \frac{n_2 - n_1}{R}.$$

32-8 Refraction at a Spherical Surface

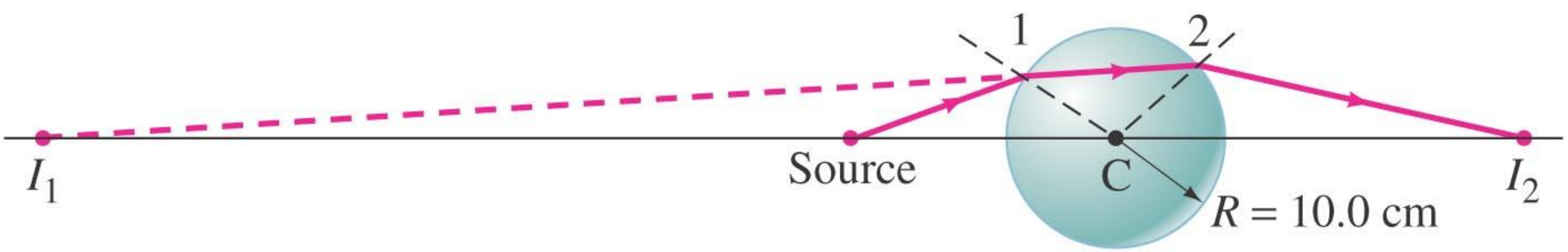
For a concave spherical interface, the rays will diverge from a virtual image.



32-8 Refraction at a Spherical Surface

Example 32-13: A spherical "lens."

A point source of light is placed at a distance of 25.0 cm from the center of a glass sphere of radius 10.0 cm. Find the image of the source.



Summary of Chapter 32

- Light paths are called rays.
- Index of refraction: $n = \frac{c}{v}$.
- Angle of reflection equals angle of incidence.
- Plane mirror: image is virtual, upright, and the same size as the object.
- Spherical mirror can be concave or convex.
- Focal length of the mirror: $f = \frac{r}{2}$.

Summary of Chapter 32

- **Mirror equation:**

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}.$$

- **Magnification:**

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}.$$

- **Real image: light passes through it.**
- **Virtual image: light does not pass through.**

Summary of Chapter 32

- **Law of refraction (Snell's law):**

$$n_1 \sin \theta_1 \;=\; n_2 \sin \theta_2 \,.$$

- **Total internal reflection occurs when angle of incidence is greater than critical angle:**

$$\sin \theta_C \;=\; \frac{n_2}{n_1} \sin 90^\circ \;=\; \frac{n_2}{n_1} .$$